Environ Earth Sci (2017) 76:762
https://doi.org/10.1007/s12665-017-7082-y

CrossMark

ORIGINAL ARTICLE

Tritium in groundwater in the Black Hills of South Dakota

Perry H. Rahn[1] · **Andrew G. Detwiler**[2] · **Arden D. Davis**[1]

Received: 12 May 2017 / Accepted: 19 October 2017 / Published online: 10 November 2017

Abstract Tritium from 1950s and 1960s atmospheric hydrogen-bomb tests was dispersed into the stratosphere and around the globe. The fallout of tritium in precipitation was especially high in the northern hemisphere, peaking during a flurry of atmospheric nuclear testing in 1963. Rainout from hydrogen-bomb tests recharged aquifers, and this maximum of tritiated water inadvertently has provided hydrogeologists with a way to establish the time of recharge because prior to hydrogen-bomb explosions, practically no tritium existed in groundwater. In 1967, the US Geological Survey took numerous Inyan Kara Group groundwater samples in the Dewey/Burdock area of the southwestern Black Hills. They found tritium concentrations exceeding 200 tritium units and determined a groundwater velocity of 4.6 m per day in the Inyan Kara aquifer, assuming the tritium originated from rainout on nearby outcrops in 1963. In 2011, the US Geological Survey took groundwater samples in the same general area as the 1967 study. These samples from the Inyan Kara Group had tritium concentrations ranging from ≤ 0 to 15.3 tritium units, much lower than the 1967 study and almost back to values expected from natural production of tritium. Because the half-life of tritium is $\sim$ 12.3 years, only 7% of the tritium generated from tests in 1963 would still be present 48 years later in 2011. The maximum tritium values found in the 2011 study are approximately the values expected from radioactive decay only; this could be interpreted that in some locations very slow groundwater movement has occurred between 1967 and 2011, while in other locations lower tritium values show there has been much faster movement. However, the great range of tritium concentrations indicates considerable variability in groundwater dispersion has occurred. This variability is caused by the complex stratigraphic units of irregular geometry and permeability in the Inyan Kara Group.

Keywords Tritium · Hydrogen bomb · Groundwater · Black Hills

✉ Perry H. Rahn
perry.rahn@sdsmt.edu

[1] Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

[2] Atmospheric and Environmental Sciences Program, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

Introduction: the hydrogen bomb and tritium fallout

The principle of the hydrogen bomb (originally referred to as the "Super," or H-bomb—Rhodes 1996) is the fusion of hydrogen to make helium. The source of hydrogen is the isotope deuterium (^{2}H). Among the products of nuclear fusion explosions is tritium (^{3}H). From 1952 to 1958, and 1961 to 1963, hundreds of American fusion and fission bombs were tested in the atmosphere at the Marshall Islands and other areas (http://www.abomb1.org/atmosphr/ustable.html, accessed 2/1/2016). Additional testing was conducted by the Union of Soviet Socialist Republics, the UK, France, China, and other nations. Although much information is classified, it is believed that more than 2000 nuclear tests were conducted (http://www.cybto/org/nuclear-testing/history-of-nuclear-testing/world-overview, accessed 2/1/2016). By the year 1993, a total of 520 atmospheric nuclear explosions had been detonated by the nuclear-armed nations worldwide, with a total yield of 217

megatons from fission weapons and 328 megatons from fusion weapons (http://en.wikipedia.org/wiki/Nuclear_weapons_testing, accessed 1/10/2017).

The by-products of these atmospheric tests were lofted into the atmosphere, some remaining in the troposphere (from 0 to 10–15 km above ground) while the rest was transported into the lower stratosphere (from the top of the troposphere up to ~ 25 km above ground) by the force of the explosion and the buoyancy of heated air mixed with explosion products. For devices detonated near a land surface, as much as 80% of the reaction products and debris, including ^{3}H, remained in the troposphere. For explosions above water surfaces, only about 20% remained in the troposphere (Canadian Nuclear Safety Commission 2009). The material remaining in the troposphere was entrained into the general circulation of the northern hemisphere, with much of it swept up in the generally eastward wind pattern. Water vapor containing tritium condensed during cloud formation when storms developed in this circulation, and some eventually precipitated to the ground. The duration of this tritium in the troposphere was on the order of a few weeks (Warneck 1988; Gat et al. 2001).

The radioactive material in the lower stratosphere remained there for many months to several years, circling the globe multiple times in a generally eastward direction. The water containing tritium remained as vapor in the stratosphere, as conditions in the stratosphere are not suitable for cloud formation except for limited times and certain locations in polar regions. Stratospheric air does not mix readily downward into the troposphere because it is warmer and more buoyant than the tropospheric air below it. However, as strong mid-latitude storm systems develop, a process called "tropopause folding" can occur in which stratospheric air is swept downward on the poleward side of the tropospheric jet stream and intrudes far into the storm system in the troposphere below (Reed 1955; Danielsen 1968; Palmen and Newton 1969). Some of this air can be mixed into regions where clouds and precipitation form, and tritium in the water vapor in the air that descended from the stratosphere can fall to the ground as part of this precipitation. The process of tropopause folding was discovered in the 1950s after nuclear bomb test products, including several very radioactive and dangerous species, were found in precipitation falling many months after the nuclear tests and thousands of miles away from the test sites (Fig. 1). In this figure, ^{3}H content of precipitation is expressed in tritium units (TU). A tritium unit corresponds to one atom of ^{3}H per 10^{18} atoms of ^{1}H—see Clark and Fritz (1997). The eventual moratorium on atmospheric testing agreed to in 1963 was in part motivated by the danger presented by global deposition of these dangerous radioactive species.

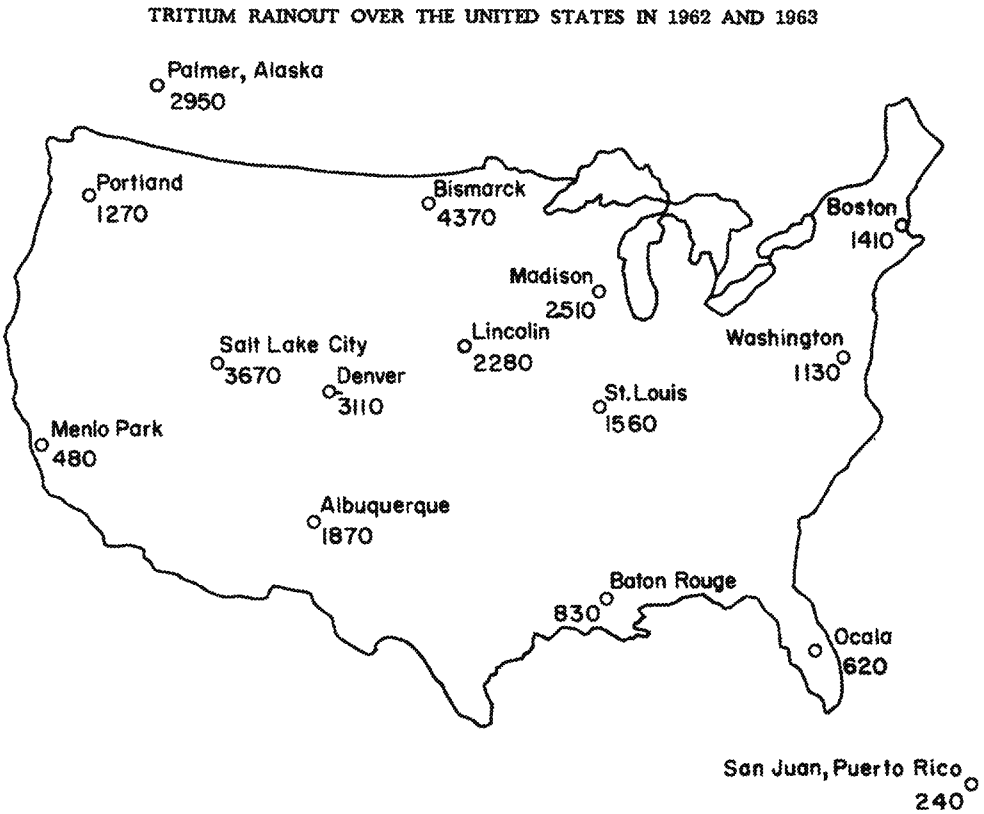
Atmospheric dispersal of ^{3}H was documented by Doney et al. (1992), who found that "… the major tritium peaks in surface rain follow by 1–2 years the atmospheric thermonuclear tests…". Monthly composite precipitation samples, analyzed for tritium from 1960 to 1986 (including tables and global maps), were described by Doney et al. (1992). Tritium precipitation samples were collected from 342 stations worldwide (Morishima et al. 1985). Figure 1 shows US tritium rainout in 1962 and 1963. Tritiated water vapor also was collected from ground level and aircraft (Mason et al. 1982). Gat et al. (2001) explained the interaction of seawater, tropospheric and stratospheric water, and the time lag between bomb test and tritiated water falling over continental areas. Figure 2 shows the record of ^{3}H in precipitation at Ottawa, Canada. The World Meteorological Organization/International Atomic Energy Agency (WMO/IAEA) has tritium concentration records for worldwide monitoring stations (IAEA 1969). The major tritium peaks in surface rain reportedly followed 1–2 years after the H-bomb tests in the late 1950s and early 1960s (Eriksson 1965; Doney et al. 1992). Gat et al. (2001) pointed out that "at the peak ^{3}H concentration during the spring 1963 the ^{3}H content of precipitation at the northern hemisphere was about 5000 TU."

Most atmospheric thermonuclear tests took place in the northern hemisphere. Immediate transport of some tritiated tropospheric water vapor from the tests in Pacific tropical areas to North America could have occurred from the atmospheric phenomenon known as an "atmospheric river" (Dettinger et al. 2016). Most ^{3}H was transported into the stratosphere, and then some of this went back into the troposphere during tropopause-folding events that occurred in late-winter/spring storm systems associated with the jet stream. For instance, Fig. 1 shows high concentrations of ^{3}H in precipitation at Bismarck, North Dakota, but lower at Menlo Park, California, where these tropopause-folding events do not occur very often.

Ottawa is the only station worldwide with ^{3}H observations prior to the start of atmospheric testing of fusion bombs. Figure 2 shows that very little tritium deposition occurred prior to the beginning of the era of atmospheric nuclear testing in 1952, followed by increasing values until 1963, the year with the peak number of tests.

Tritium as a groundwater tracer

Groundwater recharged before 1952 would be expected to have a concentration of only 2–4 TU (Freeze and Cherry 1979). H-bomb tests introduced ^{3}H into the atmosphere initially in 1952, followed by additional tests in the late 1950s and early 1960s before a moratorium on atmospheric testing was agreed upon by most of the main nuclear



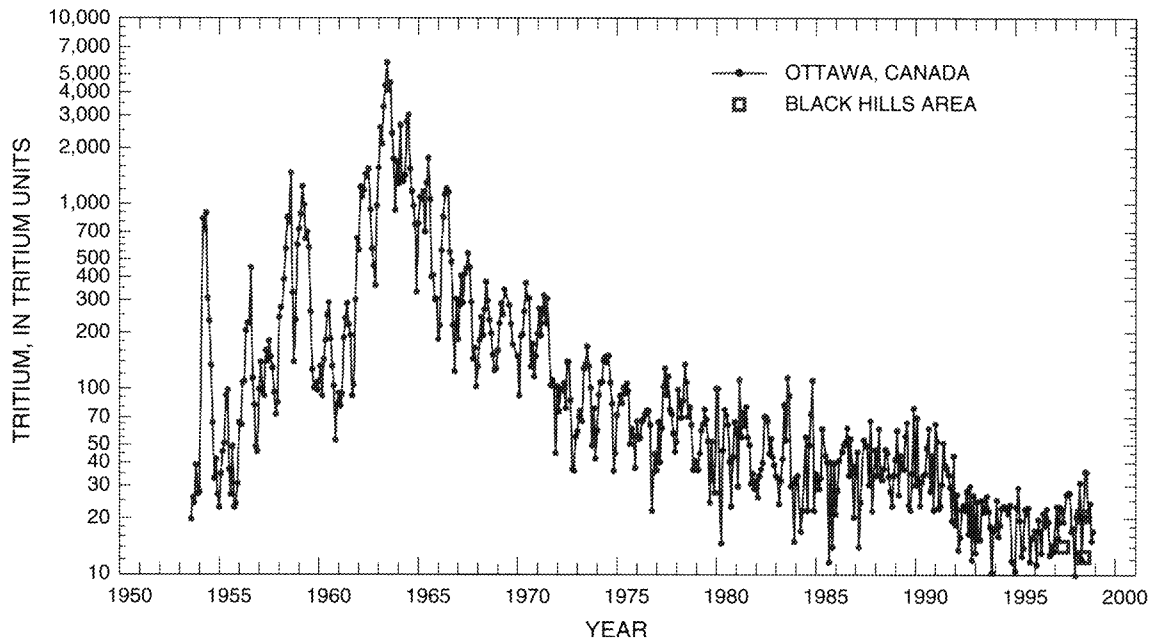


Fig. 1 Map showing weighted average ^{3}H concentrations in precipitation in TU at selected US locations during 1962 and 1963 (from Stewart and Hoffman 1966). See text for definition of TU

Fig. 2 Monthly tritium concentrations (TU) in precipitation at Ottawa, Canada. Samples from the Black Hills area of South Dakota also are shown (from Naus et al. 2001)

powers at the time. It is generally accepted that if rain recharged groundwater before 1952, or more than 50 years after the testing moratorium, it had low ^{3}H, whereas higher values indicate the water was recharged between 1952 and 1963 (Stewart and Farnsworth 1968). The increase in ^{3}H from nuclear testing in 1962–1963 was so extreme, more than an order of magnitude greater than in 1961, that the presence of ^{3}H above natural levels in water sampled from

the mid-1960s onward can be treated approximately as originating with a single pulse in 1963 (Michel 1989).

Tritium is an excellent tracer because it is nonreactive. Unlike some tracers, tritium is not retarded in groundwater flow because it constitutes part of the water itself. Furthermore, if monthly or annual averaging is done, it is observed that ^{3}H content in precipitation is remarkably uniform on scales of tens to hundreds of km (Thatcher 1962).

Tritium in Black Hills groundwater

In 1963, the average concentration of tritium in rainout over the Black Hills was approximately 3500 TU (Gott et al. 1974). Back et al. (1983) studied the chemistry of groundwater in the Madison (Pahasapa) Limestone in the Black Hills area. Samples taken in 1981 show that Cascade Spring, for example, had low tritium values (4.7 TU), indicating the water was recharged before 1952. Exceptionally high tritium concentrations were found in Rhoads, Jones, and Cleghorn Springs, all in the recharge area of the Madison Limestone. Back et al. (1983) concluded that these three springs had a large amount of post-1952 water because "... during the mid-1960s, the ^{3}H content of rainfall in the northern hemisphere was as high as 5000 TU; the average ^{3}H content of rainfall expected in the Black Hills would have been in the range of 2500 TU..." [The maximum permissible level (MPL) for drinking water is 20,000 pCi/L, equivalent to 6300 TU (Carter et al. 2002)].

Back et al. (1983) found that eastern Black Hills groundwater (Jones Spring, Cleghorn Spring, and a deep well at Ellsworth Air Force Base) was enriched with heavy isotopes of hydrogen and oxygen, whereas western Black Hills sources were depleted. This was interpreted as a function of the rainfall pattern, where rainfall coming from the northwest was isotopically depleted.

Williamson and Carter (2001) found generally low ^{3}H values in wells in the Minnelusa Formation (median 1.5 pCi/L, equivalent to 0.47 TU) and the Madison Limestone (median 6.0 pCi/L, equivalent to 1.88 TU). Naus et al. (2001) and Carter et al. (2002) showed tritium levels in Black Hills area water rising sharply from a background of about 15 TU in 1952 to maximum concentrations of about 4200 TU in 1963. Water recharged since initiation of nuclear tests in the early 1950s is considered "modern." Carter et al. (2002) found that, compared to wells in deep aquifers (that have long travel times since recharge), groundwater in headwater springs in the Madison and Minnelusa aquifers "... have high tritium concentrations, which generally indicate relatively high proportions of modern water."

Tritiated water from H-bomb tests fell on outcrops of the Inyan Kara Group in the southern Black Hills. Figure 3 shows ^{3}H data from 1967. Gott et al. (1974) collected groundwater samples in 1967 and estimated the groundwater velocity from outcrops of the sandstone members of the Inyan Kara Group to the downgradient sample locations, assuming the ^{3}H rainout originated in 1963. They noted "... widely varied rates of ground-water flow in the Inyan Kara are indicated by the tritium distribution." In the Burdock area, an exceptionally fast groundwater velocity (4.6 m per day) was determined; Gott et al. (1974) hypothesized that the fast velocity "... possibly results from artesian discharge of the Inyan Kara water into the gravels..." in the Beaver Creek–Cheyenne River lowlands areas. Rahn (2014) pointed out that this exceptionally fast groundwater velocity was not consistent with slower velocities calculated from Darcy's Law using hydraulic conductivity values obtained from nearby pumping tests.

Figure 3 shows the 1967 tritium concentrations in the Inyan Kara aquifer in the southwestern Black Hills exceeded 200 TU in some places. [Note: The half-life of tritium is $\sim$ 12.3 years (Domenico and Schwartz 1990; Lucas and Unterweger 2000). Because the time between the maximum frequency of H-bomb tests (1963) and the date of sampling (1967) was only 4 years, the radioactive decay associated with water in this region was not of major significance. Eastoe et al. (2012) pointed out that by the year 2025 or 2030, at a detection limit of 0.6 TU, tritium concentrations for groundwater studies will become indistinguishable from pre-bomb recharge.] Tritium rainout in the 1960s was in the range of 2500 TU (as noted above), but concentrations in the Inyan Kara aquifer had been reduced considerably (to $\sim$ 200 TU) at the sampled groundwater localities in 1967. It appears that the ^{3}H in the precipitation that recharged the Inyan Kara outcrops during rainouts became mixed with water in the aquifer that had been recharged by numerous prior and subsequent precipitation events with lower tritium levels.

Changes in tritium concentrations in the Dewey–Burdock area

The Dewey–Burdock area is the focus of recent environmental studies (US Nuclear Regulatory Commission 2012). Figure 4 shows year 2011 tritium concentration data in groundwater in this area. The data were collected by the US Geological Survey (Johnson 2012a, b) and show tritium concentrations in springs and wells in the Inyan Kara Group, in the underlying Jurassic Unkpapa Sandstone, and in alluvial wells. The elapsed time from year 1963 was 48 years. With a half-life of $\sim$ 12.3 years, only

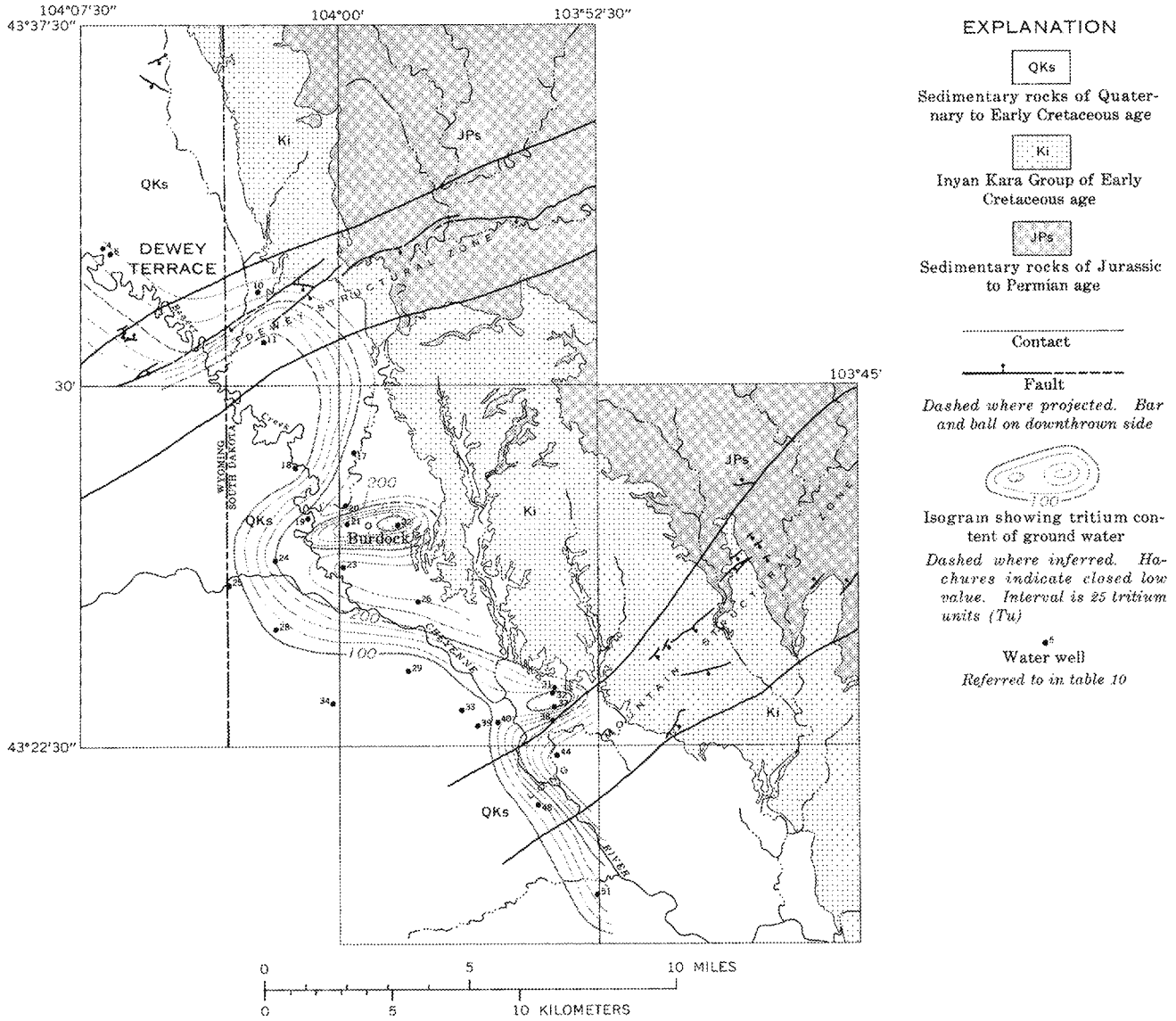


Fig. 3 Map showing tritium concentrations (TU) in groundwater in the Dewey/Burdock area in year 1967 (from Gott et al. 1974). The small black dots with an associated number (e.g., 17, 20, 21, etc.) represent numbered sampling sites of Gott et al. (1974)

approximately 7% of the ^{3}H deposited in 1963 would still be present after 48 years.

Figure 5 is a map of part of the Dewey/Burdock area showing composite TU data for the years 1967 and 2011. [Note: The Cretaceous Inyan Kara Group terminology used by Gott et al. (1974) and Rahn (2014) is used in this paper. The Inyan Kara Group contains the Fall River Formation and the underlying Lakota Formation; the Lakota Formation includes the Chilson Sandstone Member.] The ^{3}H data indicate a general reduction in the concentrations of tritium between 1967 and 2011. From Fig. 5, the average is only $\sim$ 2.7 TU for the Inyan Kara samples taken in 2011. Yet the average 1967 value in this area was $\sim$ 150 TU. Therefore, the 2011 TU values average only $\sim$ 1.8% of the 1967 values. This is lower than can be attributed only to radioactive decay, indicating groundwater movement and dilution.

Figure 5 shows four places where the 1967 sample locations are the same as (or very close to) the 2011 locations. Using the ^{3}H data published in the two US Geological Survey reports:

- Station #17 dropped from 221 to 15.3 TU,
- Station #20 dropped from 241 to − 0.3 TU,
- Station #21 dropped from 113 to 0.7 TU,
- Station #22 dropped from < 100 to 0 TU.

For Station #17, the tritium concentration was reduced to $\sim$ 6.9% of its 1967 concentration, roughly the value that would result from radioactive decay; hence, this 2011 water has a tritium concentration that would be expected

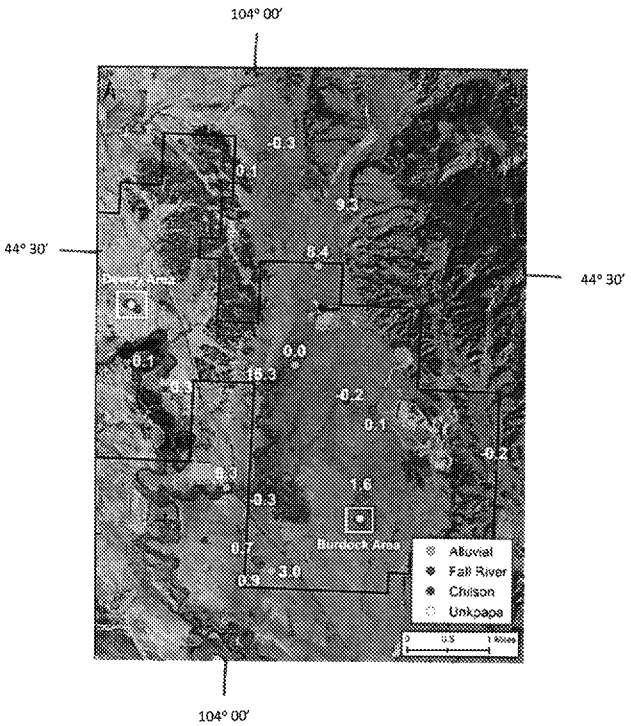


Fig. 4 Map showing tritium concentrations (TU) in groundwater in the Dewey/Burdock area in year 2011 (from Johnson 2012a)

for water that had about 200 TU in 1967 and had undergone only radioactive decay since that time. [Note: It is possible that some of the samples from 2011 were not taken from the same stratigraphic horizons in the Inyan Kara aquifer as the 1967 samples.] The other three stations above (#20, #21, and #22) show a greater decrease of ^{3}H, indicating the original 1967 water has become dispersed and/or diluted.

In the general Burdock/Dewey area, one Chilson well sampled in 2011 (Figs. 4, 5) showed 15.3 TU, and one Fall River well showed 9.3 TU. These sources were within the 200 TU areas sampled in 1967 (Fig. 3). The radioactive decay of tritium (described in the previous section) shows that in 2011 only 7% of the tritium present in 1967 should still be present in water that has neither moved nor been diluted. This is approximately what was found at these two locations, and hence these samples seem to show either that: (1) only radioactive decay has influenced the tritium concentration, with extremely slow groundwater movement, or (2) some combination of radioactive decay, dilution, dispersion, and aquifer heterogeneity was involved. Stratigraphic complexity is likely to have contributed to this enigmatic situation. A water sample taken in 1967 might have been drawn from a permeable unit, whereas a 2011 sample (at the same general location) could have come from groundwater that had dispersed into a low-permeability unit where the velocity was much slower. Unfortunately, insufficient detail is available for a definitive determination of this, based on existing information about the stratigraphic horizons that were sampled in 1967. Numerous other wells shown in Figs. 4 and 5 have TU values that are near zero; these values are interpreted as evidence that the high-tritium water that was present in 1967 has migrated away or been diluted by more modern water. Alternative explanations by Johnson (2012a) are that: (1) there is possible contamination from previous test holes, or (2) the wells with near-zero tritium concentrations indicate "... the groundwaters in those wells are likely greater than 60 years old."

In summary, a comparison of the ^{3}H data between 1967 and 2011 shows that there are places where the Inyan Kara aquifer still appears to contain tritiated recharge water from 1963 that has moved very slowly. However, there are places where it appears that the original tritiated water has moved on or has been diluted. There seems to have been much groundwater dispersion, i.e., mixing of water within the Inyan Kara units so that tritiated water became diluted with either older (pre H-bomb) water or more recently recharged water.

In places where the Inyan Kara aquifer appears to contain recharge water from 1963, a groundwater velocity could be calculated by simply assuming that water moved from the recharge point at the outcrop to a sampling point such as Station #17 (shown in Figs. 4, 5 with a 2011 tritium concentration of 15.3 TU). This location is about 3.2 km downgradient from the Inyan Kara outcrop. A travel time of 48 years would result in a groundwater velocity of about 67 m per year (about 0.2 m per day). If the recharge water moved quickly to the area near the sampling point and then some of it dispersed into a lower-permeability unit of finer-grained material, the groundwater velocity in this lower-permeability unit could be much slower. Comparison of this to the velocity of 4.6 m per day from Gott et al. (1974) indicates a wide range of groundwater velocities in the Inyan Kara aquifer. This type of situation is common with contaminants or conservative tracers in alluvial aquifers, in which contamination often is not simply flushed away as a slug; some can linger, especially in fine-grained material. Because, in Cretaceous time, much of the Inyan Kara Group's environment of deposition was fluvial and included a wide range of particle sizes, it is likely that similar controlling factors influenced the movement of tritium in the southwestern Black Hills.

The scenario described by Gott et al. (1974) is that tritiated water moves downgradient through the Inyan Kara aquifer, and near the confluence of Beaver Creek and the Cheyenne River area, it has a velocity of 4.6 m per day. Using this simple model, by year 2011 this slug of tritiated water should have passed far beyond the Dewey/Burdock area. But that does not seem to have happened. Rather,

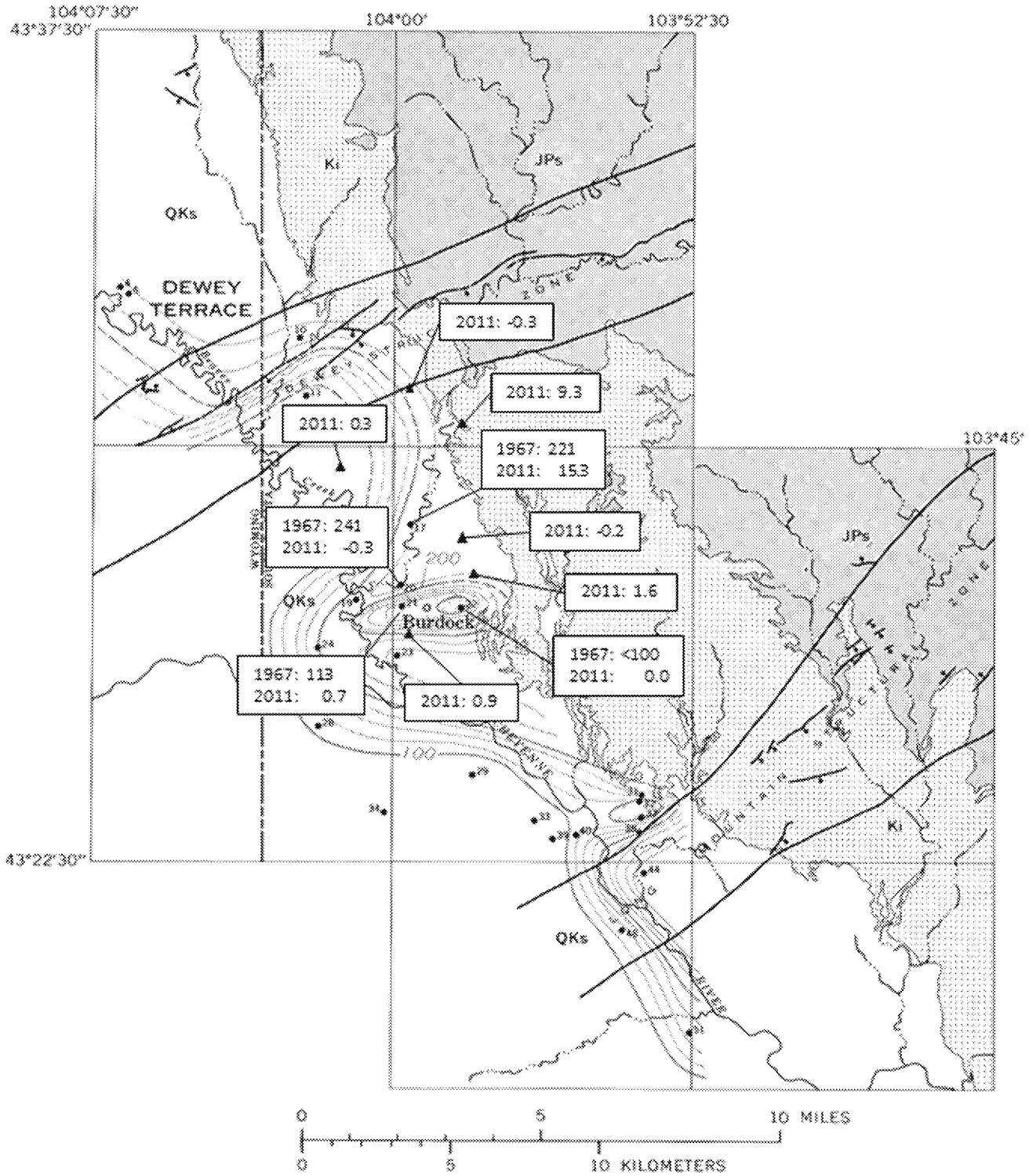


Fig. 5 Map showing 1967 and 2011 tritium concentrations in groundwater in the Inyan Kara Group. This map is a modification of part of Fig. 3 showing 1967 TU isograms. The four black circle locations (17, 20, 21, and 22) show 1967 Inyan Kara sampling sites, with 2011 samples from the same site or nearby. The six delta locations show tritium concentrations from 2011 Inyan Kara sampling sites of Johnson (2012a)

some of the tritiated water seems to have remained in the same general location where it was originally observed in 1967. In addition to this situation, it appears that dilution with nontritiated water has occurred as well as dispersion

through the complex sandstone channels in the Chilson and other members of the Inyan Kara aquifer. Water also seems to have leaked upward into the alluvial units. Figure 6 is a potentiometric map of the Inyan Kara aquifer. In the Dewey area, the potentiometric surface slopes southwesterly at a hydraulic gradient of approximately 0.01. Based on potentiometric information published by the US Geological Survey (Strobel et al. 2000; Carter et al. 2002), the head in the Inyan Kara aquifer is above the land surface in parts of the area, especially in the valleys of creeks and near the Cheyenne River. Several flowing artesian wells are shown on the US Geological Survey's 1:24,000-scale Burdock and Dewey topographic quadrangle maps of the area (US Geological Survey 1950, 1951), so leakage to alluvium is likely. Davis (1986) used field mapping, aerial photography, and drilling data in the Black Hills to delineate alluvial aquifer heterogeneity in a model of groundwater flow and solute transport and demonstrated improved simulations of dispersion as a result (Fetter 1999).

Discussion

Tritium, the inadvertent result of thermonuclear bomb tests, provides a tool to study groundwater in the southern Black Hills. Wells and springs were sampled and analyzed for tritium by the US Geological Survey in 1967 and showed groundwater concentrations greater than 200 TU at places (Gott et al. 1974). Assuming tritiated water fell on outcrops of the Inyan Kara Group in 1963, a maximum velocity of 4.6 m per day was determined by the US Geological Survey, based on the distance traveled in 4 years.

In 2011, the US Geological Survey took samples in the same area and found tritium concentrations varied greatly, from approximately zero to 15.3 TU. The higher value of 15.3 TU represents a decline to 7% of the 1967 values by 2011; this is approximately the concentration that would result if the water at or near this sampling location in 1967 had undergone only radioactive decay of tritium since that time. This indicates that groundwater velocities vary greatly in different parts of the aquifer. It was not simply a slug of tritiated groundwater moving at 4.6 m per day through the aquifer, because by the year 2011 this fast-moving water would be many kilometers downgradient unless there was a great change in hydrogeologic conditions. The interpretation of the great range of TU (especially the 2011 data) is challenging. In some parts of the aquifer, there could be extremely slow groundwater velocities and nearly stagnant water, yet there are other places where rapid movement and dispersion have occurred.

Originally simply described as the "Dakota Sandstone" (Darton 1909), this famous artesian aquifer is now called the Inyan Kara Group in the Black Hills area. It has been studied by numerous hydrogeologists (e.g., Keene 1973; Bredehoeft et al. 1983; Case 1984). The tritium concentrations show that the Inyan Kara Group is not a simple, homogeneous aquifer in which a slug of tritiated water

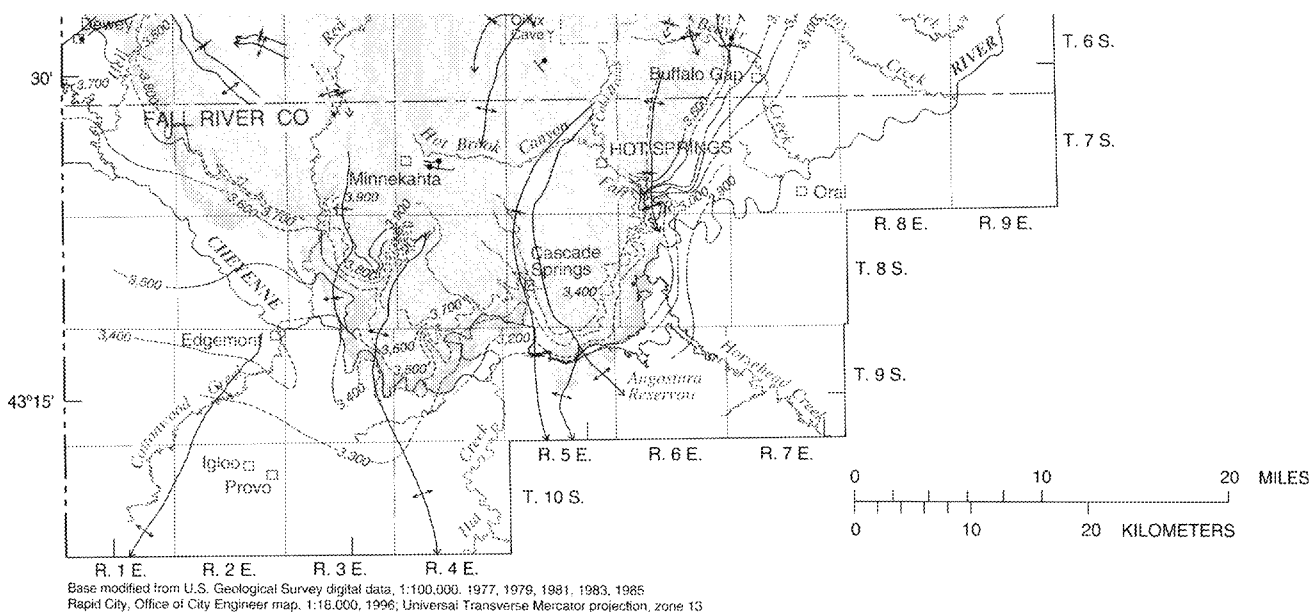


Fig. 6 Potentiometric map of the Inyan Kara aquifer in the southern Black Hills (from Carter et al. 2002). In the Dewey area, the potentiometric surface slopes southwesterly at a hydraulic gradient of approximately 0.01. The potentiometric contours are in units of feet above sea level. The yellow color indicates the outcrop of the Inyan Kara Group

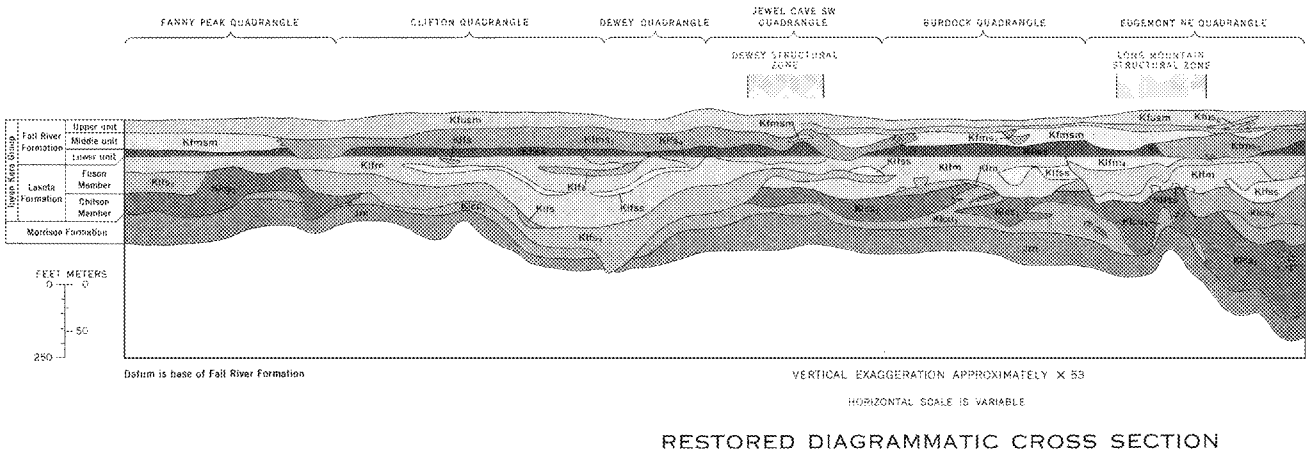


Fig. 7 Diagrammatic cross section showing stratigraphy of the Inyan Kara Group in the southwestern Black Hills. [Note: This cross section was originally published as part of Plate 1 from Gott et al. (1974).] The lower sandstone member of the Fall River Formation is shown as $Kfms_5$, and the Chilson (sandstone) Member of the Lakota Formation is shown as $Klcs_1$. The line of cross section is northwest to southeast along the outcrop of the Inyan Kara Group, on Fig. 3

would move like a tracer in a laboratory experiment with uniform material.

The hydrogeology of the Inyan Kara aquifer is controlled by its complex stratigraphy. This aquifer includes facies involving sandstone, shale, coal, and limestone members (Fig. 7). Schoon (1971), for example, described Lakota sedimentary facies originally deposited in a continental environment as the Cretaceous sea encroached from the northwest. Dahlstrom and Fox (1995) showed the Lakota Formation in the southwestern flank of the Black Hills is about 150 m thick and contains three fluvial sandstone units.

The anisotropic nature of the stratigraphic units is an additional hydrogeologic factor. The permeable sandstone units are fluvial channel sands that have irregular geometry and anisotropic transmissivity. For example, a pumping test in the Lakota Formation at Wall, South Dakota, utilized four observation wells and showed "... a principal transmissivity of 2650 gallons per day per foot (32.9 m^2/day), oriented in a north 35° west direction" (Rahn 1992). The hydrogeologic regime is complicated by secondary permeability that developed along fractures in the Lakota Formation. The sandstone units in the Inyan Kara Group are the primary conduits though which groundwater moves, and the 1967 and 2011 water samples are believed to have come largely from these units. Leakage between the Chilson Member of the Lakota Formation and the overlying Fall River Formation is another hydrogeologic process that has been documented by previous pumping tests (Boggs and Jenkins 1980).

Groundwater velocities in the Inyan Kara aquifer can vary from a few meters per year (Rahn, 2014) or slower in shale or silty layers, to 4.6 m per day or faster, in permeable sandstone channels. Well production rates also vary greatly. Carter et al. (2002) showed that the median production of Inyan Kara wells in the Black Hills is about 68 L per minute and the mean is about 115 L per minute, but values range from less than 0.8 L per minute to thousands of liters per minute. In the Dewey area, Boggs (1983) reported a pumping rate of 1870 L per minute during an 11-day pumping test of a well in the Chilson Member of the Lakota Formation; in that test, the transmissivity was 55 m^2/day and the storage coefficient was 0.0001. In the Burdock area, Boggs and Jenkins (1980) conducted a 3-day pumping test of a well in the Lakota Formation, with a pumping rate of about 760 L per minute. The transmissivity of the Lakota aquifer at that location was 17 m^2/day, with a storage coefficient of 0.0001. Boggs and Jenkins (1980) also conducted a pumping test for the Fall River Formation in the Burdock area, with a pumping rate of about 32 L per minute. The transmissivity determined in that test was 5 m^2/day, and the storage coefficient was 1.4×10^{-5}. Clearly, the Inyan Kara aquifer is extremely heterogeneous. Permeable sandstone layers and fractured zones in the aquifer can provide large production rates and fast groundwater velocities, while other zones are finer-grained and much less permeable. The large contrasts of hydraulic conductivity at boundaries between sandstone and shale cause sharp changes in the magnitude and direction of groundwater flow velocities in the aquifer. This, in turn, results in greater dispersion and a wide range of tritium concentrations. Thus, the aquifer's variability helps explain the challenging range of tritium data compiled here.

Conclusions

The tritium data presented in this paper show that future hydrogeologic studies of the Inyan Kara Group will require a firm knowledge of stratigraphy and its influence on

groundwater flow conditions. The cross section on Fig. 7 illustrates that the Inyan Kara aquifer has a complex stratigraphy, with extreme lateral and vertical heterogeneity that results in great variation of groundwater velocities and dispersion. The aquifer contains interbedded sandstone and shale, along with coal and limestone. Sandstone lenses in the Chilson Member of the Lakota Formation are fluvial, with irregular geometry and anisotropic flow conditions. The widely contrasting lithologies in the Inyan Kara Group result in sharp differences in the magnitude and direction of groundwater flow, causing a large range of concentrations and extreme dispersion of tritium.

Tritium's usefulness as a tracer from 1960s hydrogen-bomb fallout will be limited after the year 2030 because of its short half-life, so future tracer studies of transport and dispersion in the Inyan Kara aquifer will depend on other radionuclides, dye, or alternative methods.

References

Back W, Hanshaw BB, Plummer LN, Rahn PH, Rightmire CT, Rubin M (1983) Process and rate of dedolomitization: mass transfer and ^{14}C dating in a regional carbonate aquifer. Geol Soc Am Bull 94:1415

Boggs JM (1983) Hydrogeologic investigations at proposed uranium mine near Dewey, South Dakota. Tennessee Valley Authority Report WR-28-2-520-128, p 54

Boggs JM, Jenkins AM (1980) Analysis of aquifer tests conducted at the proposed Burdock uranium mine site—Burdock, South Dakota. Tennessee Valley Authority Report WR28-1-520-109, p 73

Bredehoeft JD, Neuzil CE, Milly PCD (1983) Regional flow in the Dakota aquifer: a study of the role of confining layers. US Geol Survey Water-Supply Paper 2237, p 45

Canadian Nuclear Safety Commission (2009) Investigation of the environmental fate of tritium in the atmosphere. http://nuclearsafety.gc.ca/pubs_catalogue/uploads/Investigation_of_Environmental_Fate_of_Tritium_in_the_Atmosphere_INFO-0792_e.pdf. Accessed 1 Oct 2017

Carter JM, Driscoll DG, Williamson JE, Lindquist VA (2002) Atlas of water resources in the Black Hills area, South Dakota. US Geol Survey Hydrol Inv Atlas HA-747, p 120

Case HL (1984) Hydrology of the Inyan Kara and Dakota-Newcastle aquifer system, South Dakota. In: Jorgenson DC, Signor DC (eds) Proc of the geohydrology of the Dakota aquifer symposium. Nat Water Well Assoc, pp 147–165

Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis Publishers, New York, p 328

Dahlstrom DJ, Fox JE (1995) Fluvial architecture of the Lower Cretaceous Lakota Formation, southwestern flank of the Black Hills uplift, South Dakota. US Geol Survey Bull 1917-S, p 20

Danielsen EF (1968) Stratospheric-tropospheric exchange based upon radioactivity, ozone, and potential vorticity. J Atmos Sci 25:502–518

Darton NH (1909) Geology and underground water of South Dakota. US Geol Survey Water-Supply Paper 227, p 156

Davis AD (1986) Deterministic modeling of dispersion in heterogeneous permeable media. Ground Water 24(5):609–615

Dettinger M, Ralph FM, Lavers D (2016) Setting the stage for a global science of atmospheric rivers. EOS Earth Space Sci News 97(1):7

Domenico PA, Schwartz FW (1990) Physical and chemical hydrogeology. Wiley, New York, p 824

Doney SC, Glover DM, Jenkins WJ (1992) A model function of the global bomb tritium distribution in precipitation, 1960–1986. J Geophys Res 97(C4):5481–5492

Eastoe CJ, Watts CJ, Ploughe M, Wright WE (2012) Future use of tritium in mapping pre-bomb groundwater volumes. Ground Water 50(1):87–93

Eriksson E (1965) An account of the major pulses of tritium and their effect in the atmosphere. Tellus 17:118–130

Fetter CW (1999) Contaminant hydrogeology, 2nd edn. Waveland Press, Long Grove, p 500

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Englewood Cliffs, p 604

Gat JR, Mook WG, Meijer HAJ (2001) Tritium in the atmosphere. Internat Atomic Energy Agency: Environmental Isotopes in the Hydrological Cycle, Principles and Application, 2, Atmospheric Water, pp 209–232

Gott GB, Wolcott DE, Bowles CG (1974) Stratigraphy of the Inyan Kara Group and localization of uranium deposits, southern Black Hills, South Dakota and Wyoming. US Geol Survey Prof Paper 763, p 57

International Atomic Energy Agency (IAEA) (1969) Environmental isotope data 1: world survey of isotope concentration in precipitation (1953–1963). Tech Rept Ser, IAEA, p 96

Johnson RH (2012a) Update on USGS research at the proposed Dewey Burdock uranium in situ recovery mine, Edgemont, South Dakota. Presentation to EPA Region 8 in Denver, CO. http://crustal.usgs.gov/projects/UREP/2-Groundwater-geochemistry-Dewey-Burdock-Johnson-final.pdf. Accessed 22 Feb 2012

Johnson RH (2012b) Geochemical data from groundwater at the proposed Dewey Burdock uranium in situ recovery mine, Edgemont, South Dakota. US Geol Survey Open-File Report 2012-1070, p 11

Keene JR (1973) Ground-water resources of the western half of Fall River County, South Dakota. South Dakota Geol Survey Rept of Inv 109, p 82

Lucas LL, Unterweger MP (2000) Comprehensive review and critical evaluation of the half-life of tritium. J Res Natl Inst Stand Technol 105(4):541. https://doi.org/10.6028/jres.105.043

Mason AS, Hut G, Telegades K (1982) HTO and ^{95}Zr residence times. Tellus 34:369–375

Michel RL (1989) Tritium deposition over the continental United States, 1953–1983. In: Proceedings of Baltimore symposium, May, 1989, international association of hydrological sciences, international union of geodesy and geophysics. http://www.iugg.org

Morishima H, Kawai H, Koya T, Niwa T (1985) The trends of global tritium precipitations. J Radiat Res 26:283–312

Naus CA, Driscoll DG, Carter JM (2001) Geochemistry of the Madison and Minnelusa aquifers in the Black Hills area, South Dakota. US Geol Survey Water-Resources Inv Rept 01-4129, p 118

Palmen EH, Newton CW (1969) Atmospheric circulation systems: their structure and physical interpretation. Academic Press, New York, p 603

Rahn PH (1992) Aquifer hydraulics in a deep confined Cretaceous aquifer at Wall, South Dakota. In: Proceedings of assoc engineering geologists, 35th annual meeting, Los Angeles, CA, pp 409–418

Rahn PH (2014) Permeability of the Inyan Kara Group in the Black Hills area and its relevance to a proposed in situ leach uranium mine. Proc South Dakota Acad Sci 93:15–32

Reed RJ (1955) A study of a characteristic type of upper-level frontogenesis. J Meteorol 12:226–237

Rhodes R (1996) Dark sun, the making of the hydrogen bomb. Simon and Schuster, New York, p 731

Schoon RA (1971) Geology and hydrology of the Dakota Formation in South Dakota. South Dakota Geol Survey Rept of Inv 104, p 41

Stewart GL, Farnsworth RK (1968) United States tritium rainout and its hydrologic implications. Water Resour Res 4:273–289

Stewart GL, Hoffman CM (1966) Tritium rainout over the United States. US Geol Surv Circ 520:11

Strobel ML, Galloway JM, Hamade GR, Jarrell GJ (2000) Potentiometric surface of the Inyan Kara aquifer in the Black Hills area, South Dakota. U.S. Geological Survey Hydrol Inv Atlas HA-745-A, 2 pl

Thatcher LL (1962) The distribution of tritium fallout in precipitation over North America. Int Assoc Sci Hydrol Bull 7(2):48–58. https://doi.org/10.1080/02626666209493255

US Geological Survey (1950) Burdock, South Dakota, topographic quadrangle; 1:24,000 scale

US Geological Survey (1951) Dewey, Wyo—S Dakota, topographic quadrangle; 1:24,000 scale

US Nuclear Regulatory Commission (2012) Environmental impact statement for the Dewey–Burdock project in Custer and Fall River counties, South Dakota: Supplement to the generic environmental impact statement for in situ leach uranium milling facilities. NUREG-1910, Supplement 4(1)

Warneck P (1988) Chemistry of the natural atmosphere. Academic Press, New York, p 757

Williamson JE, Carter JM (2001) Water-quality characteristics in the Black Hills area, South Dakota. US Geol Survey Water-Resources Inv Rept 01-4194, p 196